PART 1: TEMPERATURE, HEAT AND THERMAL EXPANSION

1.1 Learning Objectives

After studying this part, students will be able to:

- Understand the concepts of temperature and thermal equilibrium.
- Distinguish between heat and temperature.
- Explain different temperature scales.
- Convert temperatures between Celsius, Fahrenheit and Kelvin scales.
- Understand thermal expansion.
- Derive expressions for linear, area and volume expansion.
- Understand the relation between coefficients of expansion.
- Apply thermal expansion concepts to numerical problems.
- Understand practical applications of thermal expansion.

1.2 Thermal Properties of Matter

Matter changes its physical behaviour when its temperature changes.
Some important thermal effects are:

- Expansion of solids, liquids and gases
- Change in temperature
- Change of state
- Heat transfer
- Specific heat
- Latent heat
- Thermal conductivity

These properties are collectively studied under the **thermal properties of matter**.

1.3 Temperature

Temperature is a physical quantity that indicates the degree of hotness or coldness of a body.
At the microscopic level, temperature is related to the average kinetic energy of the random motion of particles.
For an ideal gas, the average translational kinetic energy per molecule is directly proportional to absolute temperature.
Thus, qualitatively:
Temperature ↑ → Average molecular kinetic energy ↑

1.4 Heat

Heat is energy transferred from one body to another because of a temperature difference.
Heat always flows spontaneously from a body at higher temperature to a body at lower temperature until thermal equilibrium is reached.

Important Distinction

Temperature describes the thermal state of a body.
Heat is energy transferred because of a temperature difference.
Therefore, heat and temperature are **not the same physical quantity**.

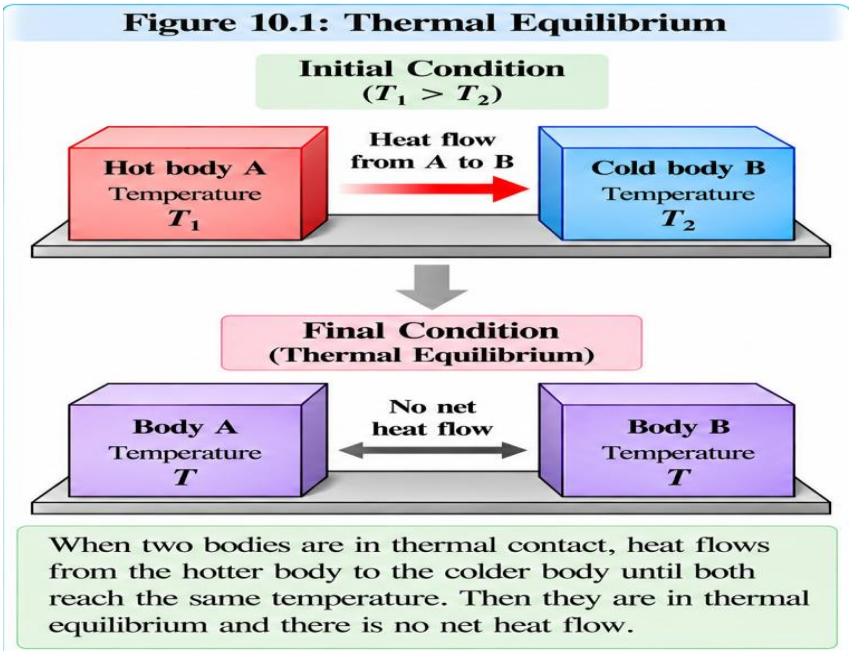
1.5 Thermal Equilibrium

Suppose two bodies at different temperatures are placed in thermal contact.
Heat flows from the hotter body to the colder body.
After sufficient time, their temperatures become equal.
At this stage, they are said to be in **thermal equilibrium**.

Definition

Two bodies are in thermal equilibrium if there is no net heat transfer between them when they are in thermal contact.

Figure 10.1: Thermal Equilibrium



When two bodies are in thermal contact, heat flows from the hotter body to the colder body until both reach the same temperature. Then they are in thermal equilibrium and there is no net heat flow.

1.6 Thermometers

A thermometer is an instrument used to measure temperature.
It uses a measurable physical property that changes with temperature.
Such a property is called a **thermometric property**.

Examples

Thermometer	Thermometric Property
Mercury thermometer	Volume of mercury
Resistance thermometer	Electrical resistance
Thermocouple	Thermoelectric emf
Gas thermometer	Pressure or volume
Radiation thermometer	Thermal radiation

1.7 Temperature Scales

The commonly used temperature scales are:

1. Celsius scale
2. Fahrenheit scale
3. Kelvin scale

1.7.1 Celsius Scale

The Celsius scale is defined using two fixed points:

- Lower fixed point = **0°C**
- Upper fixed point = **100°C**

The interval between them is divided into 100 equal parts.
Thus,
1°C = 1 kelvin temperature interval
although the numerical zero points are different.

1.7.2 Fahrenheit Scale

The Fahrenheit scale has:

- Lower fixed point = **32°F**
- Upper fixed point = **212°F**

The interval is divided into 180 equal parts.

1.7.3 Kelvin Scale

The Kelvin scale is the SI scale of thermodynamic temperature.
Its unit is **kelvin (K)**.
The triple point of water is assigned: **273.16 K**
The temperature scale is related to Celsius by: **T(K) = t(°C) + 273.15**
Therefore: **0°C = 273.15 K** and **100°C = 373.15 K**
For many school-level calculations, **273** is used as an approximation.

1.8 Temperature Conversion

The relationship between Celsius and Fahrenheit scales is:

$$C/5 = (F - 32)/9$$

Therefore,

$$F = (9/5)\,C + 32$$

And

$$C = (5/9)(F - 32)$$

Celsius–Kelvin Relation

K = C + 273.15 or approximately, **K ≈ C + 273**

Fahrenheit–Kelvin Relation

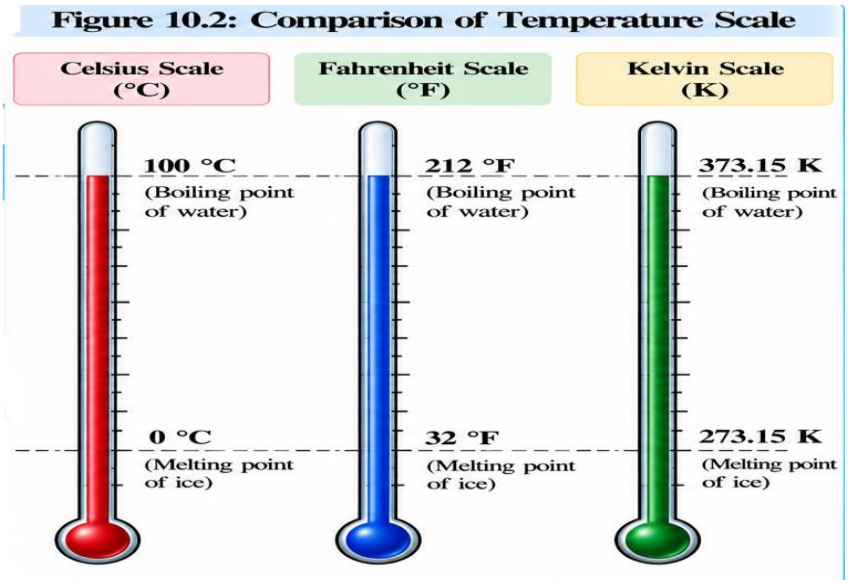
Using Celsius as an intermediate scale: **K = (5/9)(F − 32) + 273.15**

1.9 General Temperature-Scale Relation

Suppose a temperature is represented by readings:

- X on one scale
- Y on another scale

If the lower and upper fixed points are known, the general relation is obtained by comparing the fractional intervals.
For Celsius and Fahrenheit: **C/100 = (F − 32)/180**
Which gives: **C/5 = (F − 32)/9**



1.10 Solved Example 1 — Temperature Conversion

Convert **25°C** into Fahrenheit.
Using:
F = (9/5) C + 32
Therefore,
F = (9/5)(25) + 32 = 45 + 32 = 77°F
Answer: 25°C = 77°F

1.11 Solved Example 2 — Celsius to Kelvin

Convert **27°C** into Kelvin.
Using:
K = C + 273.15
Therefore,
K = 27 + 273.15 = 300.15 K
Approximately: **K ≈ 300 K**

1.12 Important Temperature Conversions

Celsius	Fahrenheit	Kelvin
0°C	32°F	273.15 K
25°C	77°F	298.15 K
100°C	212°F	373.15 K
−273.15°C	−459.67°F	0 K

Important

0 K = −273.15°C
This is called **absolute zero**.

1.13 Absolute Zero

Absolute zero is the lowest limiting temperature of the thermodynamic temperature scale.
Its value is: **0 K = −273.15°C**

At temperatures approaching absolute zero, the thermal motion of particles becomes extremely small.
However, according to quantum mechanics, it is not correct to interpret this as all microscopic motion simply becoming zero.

Important Exam Point

Kelvin temperature cannot be negative.

Important:

1. Change in temperature in degree Celsius = Change in temperature in Kelvin

$$\boxed{\Delta \boldsymbol{C} = \Delta \boldsymbol{K}}$$

Because, $C_1 = K_1 - 273.15$ and $C_2 = K_2 - 273.15$
Therefore, $C_2 - C_1 = \Delta C = K_2 - K_1 = \Delta K$

2. Change in degree Fahrenheit = (9/5) Change in degree Celsius

$$\boxed{\Delta \boldsymbol{F} = (\boldsymbol{9/5})\Delta \boldsymbol{C}}$$

Because,

$$\frac{(F_1 - 32)}{9} = \frac{C_1}{5} \Rightarrow F_1 = \frac{9}{5}C_1 + 32$$

And,

$$\frac{(F_2 - 32)}{9} = \frac{C_2}{5} \Rightarrow F_2 = \frac{9}{5}C_2 + 32$$

Hence,

$$F_2 - F_1 = \Delta F = \frac{9}{5}(C_2 - C_1) = \frac{9}{5}\Delta C$$

1.14 Thermal Expansion

Most substances expand when heated and contract when cooled.
This phenomenon is called **thermal expansion**.
The expansion occurs because increasing temperature generally increases the average separation between particles.
Thermal expansion is particularly important in solids, where three types are considered:

1. Linear expansion
2. Superficial or area expansion
3. Cubical or volume expansion

1.15 Linear Expansion

Consider a rod of original length $\mathbf{L_0}$ at temperature $\mathbf{T_0}$.
When its temperature increases by $\mathbf{\Delta T}$, its length increases by $\mathbf{\Delta L}$, then

$$\mathbf{\Delta L = L - L_o}$$

Experimentally,
$\mathbf{\Delta L \propto L_0}$ and $\mathbf{\Delta L \propto \Delta T}$
Hence: $\mathbf{\Delta L \propto_{L0\Delta T}}$
Introducing a constant of proportionality α:

$$\mathbf{\Delta L = \alpha L_0 \Delta T}$$

Where α is called the **coefficient of linear expansion**.

1.16 Coefficient of Linear Expansion

From: $\Delta L = \alpha L_0 \Delta T$
We get: $\alpha = \Delta L/(L_0 \Delta T)$

Definition

Coefficient of linear expansion is the fractional increase in length per unit rise in temperature.

SI Unit: K^{-1}

It may also be expressed as: $°C^{-1}$
Because a temperature interval of 1 K is equal to an interval of 1°C.

Dimensions: $[\alpha] = K^{-1}$

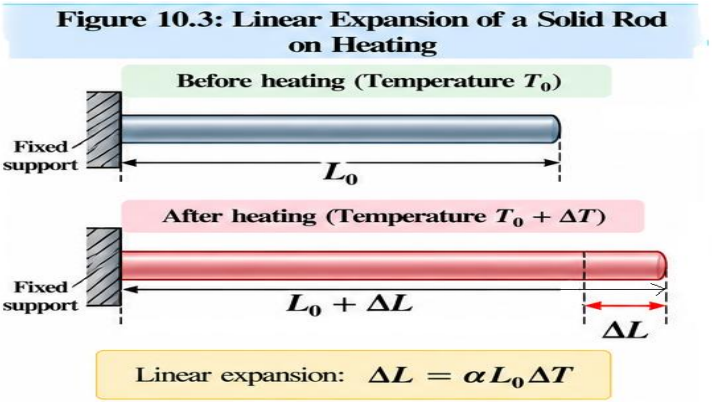


Figure 10.3: Linear Expansion of a Solid Rod on Heating

1.17 Final Length after Heating

Since: $\Delta L = \alpha L_0 \Delta T$ and $\Delta L = L - L_0$
We obtain: $L - L_0 = \alpha L_0 \Delta T$
Therefore: $L = L_0 (1 + \alpha \Delta T)$
This formula is useful for numerical problems.

1.18 Factors Affecting Linear Expansion

From: $\Delta L = \alpha L_0 \Delta T$
The change in length depends on:

1. Original length L_0
2. Temperature change ΔT
3. Nature of material through α

Thus: $\Delta L \propto L_0$ **and** $\Delta L \propto \Delta T$
For a given temperature change: $\Delta L \propto \alpha$

1.19 Thermal Expansion of Area

Consider a rectangular sheet having initial dimensions: $L_0 \times B_0$
Initial area: $A_0 = L_0 B_0$
After heating, both length and breadth increase.
For an isotropic material: $\Delta L = \alpha L_0 \Delta T$ and $\Delta B = \alpha B_0 \Delta T$
The fractional change in area is approximately: $\Delta A/A_0 = 2\alpha\Delta T$
Therefore: $\Delta A = 2\alpha A_0 \Delta T$

1.20 Coefficient of Area Expansion

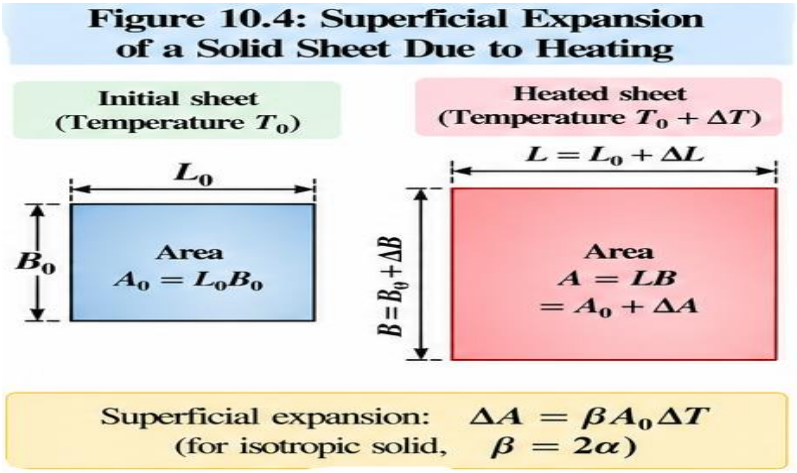
Definition

Coefficient of area expansion is the fractional increase in area per unit rise in temperature.
Therefore:

$$\beta = \Delta A/(A_0 \Delta T)$$

For an isotropic solid: $\beta = 2\alpha$
These relations are valid for small temperature changes and isotropic solids, under the usual approximation.

SI Unit: K^{-1}



1.21 Thermal Expansion of Volume

Consider a solid of initial volume: $\mathbf{V_0}$
When its temperature increases by $\mathbf{\Delta T}$, its volume increases by: $\mathbf{\Delta V}$
Experimentally: $\mathbf{\Delta V \propto V_0}$ and $\mathbf{\Delta V \propto \Delta T}$
Therefore: $\mathbf{\Delta V = \gamma V_0 \Delta T}$
Where, γ is the **coefficient of volume expansion**.

1.22 Coefficient of Volume Expansion

From: $\mathbf{\Delta V = \gamma V_0 \Delta T}$
We obtain: $\mathbf{\gamma = \Delta V/(V_0 \Delta T)}$

Definition

Coefficient of volume expansion is the fractional increase in volume per unit rise in temperature.

SI Unit: $\mathbf{K^{-1}}$

Dimensions: $\mathbf{[\gamma] = K^{-1}}$

1.23 Relation Between α, β and γ

For an isotropic solid:

$$\alpha = \alpha$$

$$\beta = 2\alpha$$

$$\gamma = 3\alpha$$

Therefore:

$$\boxed{\boldsymbol{\alpha : \beta : \gamma = 1 : 2 : 3}}$$

1.24 Derivation of γ = 3α

Consider a cube of side L.
Initial volume: $\mathbf{V = L^3}$
After heating: $\mathbf{L' = L(1 + \alpha \Delta T)}$

Therefore,

$$V' = [L(1 + \alpha\Delta T)]^3$$

For small expansion:

$$(1 + \alpha\Delta T)^3 \approx 1 + 3\alpha\Delta T$$

Hence,

$$V' \approx V(1 + 3\alpha\Delta T)$$

Therefore,

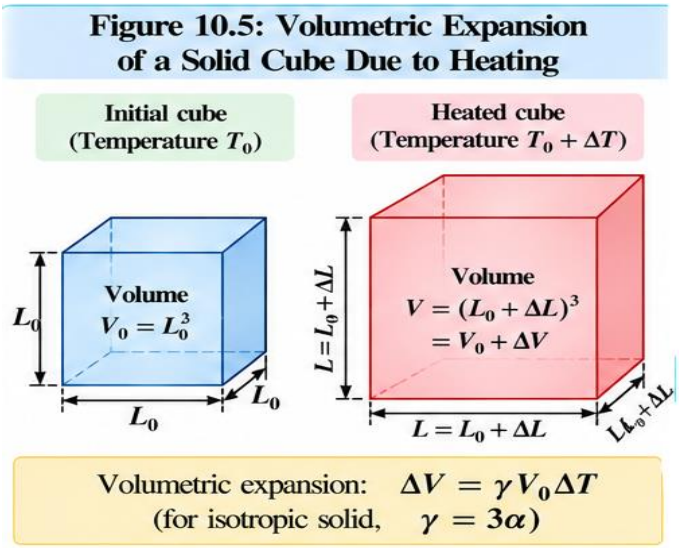
$$\Delta V = 3\alpha V\Delta T$$

Comparing with:

$$\Delta V = \gamma V\Delta T$$

We obtain:

$$\boxed{\gamma = 3\alpha}$$



1.25 Important Note on Isotropic Solids

The relations $\beta = 2\alpha$ and $\gamma = 3\alpha$ apply to **isotropic materials**, for which thermal expansion is the same in all directions.

For anisotropic materials, expansion may differ along different directions.

1.26 Thermal Expansion of a Hole

A very important conceptual question:

What happens to a hole in a metal plate when the plate is heated?

Answer

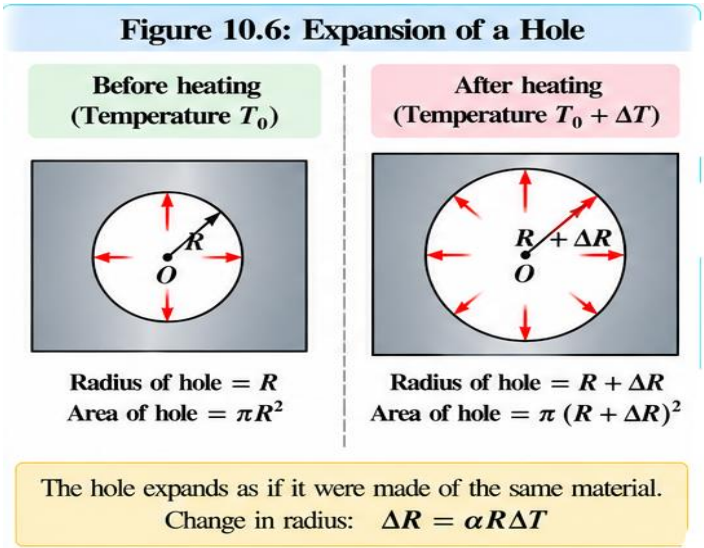
The hole **expands**.

If the plate is heated uniformly, every linear dimension increases.

Therefore, the diameter of the hole also increases.

Important Principle

A hole in a heated plate expands as if it were made of the same material.

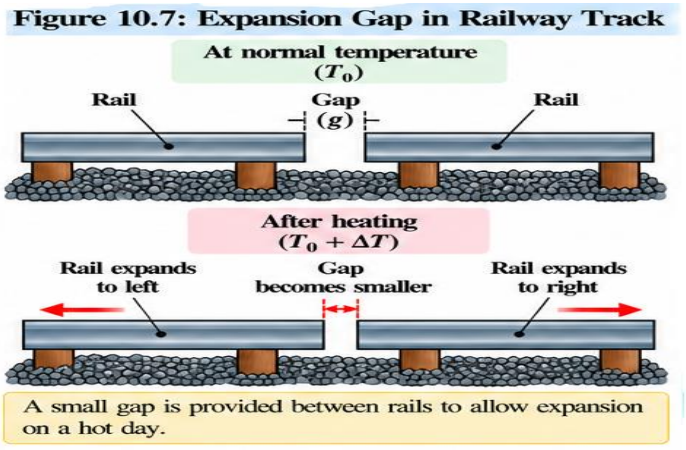


1.27 Thermal Expansion and Gaps

Thermal expansion must be considered when constructing:

- Railway tracks
- Bridges
- Long pipelines
- Metal roofs
- Concrete structures

If expansion is not allowed, very large forces can develop.
Therefore, suitable gaps or expansion joints are provided.

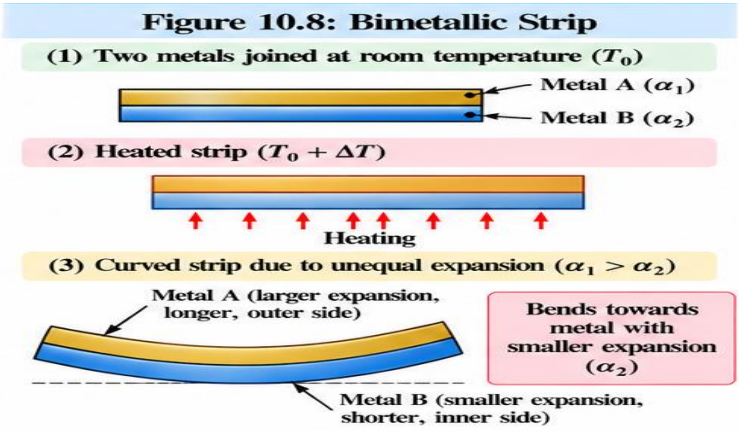


1.28 Bimetallic Strip

A bimetallic strip consists of two different metals firmly joined together.
The two metals have different coefficients of linear expansion.
When heated, one metal expands more than the other.
Therefore, the strip bends.

Applications

- Thermostats
- Automatic temperature-control devices
- Electric irons
- Fire alarms
- Temperature switches



1.29 Thermal Stress

Suppose a rod is heated but is completely prevented from expanding.
The rod experiences internal stress called **thermal stress**.
The free thermal strain would have been:

$$\textbf{Strain} = \alpha\Delta T$$

Using:

$$\textbf{Stress} = Y \times \textbf{Strain}$$

We obtain:
Thermal stress:

$$|\sigma| = Y\alpha|\Delta T|$$

Where, Y is Young's modulus.

Important

For a rod prevented from expanding on heating, the induced thermal stress is **compressive**.
For a rod prevented from contracting on cooling, the induced thermal stress is **tensile**.

1.30 Thermal Expansion of Liquids

Liquids do not have a definite shape, so only volume expansion is considered.
For a liquid: $\Delta V = \gamma V_0 \Delta T$
Where, γ is the coefficient of volume expansion of the liquid.
However, when a liquid is heated inside a container, the observed expansion depends on both:

- Expansion of the liquid
- Expansion of the container

1.31 Real and Apparent Expansion of a Liquid

Suppose a liquid is heated in a container.
The liquid expands, but the container also expands.

Therefore, the increase in volume observed relative to the container is less than the actual increase in volume of the liquid.

Real Expansion

Actual increase in volume of the liquid

Apparent Expansion

Increase in volume observed relative to the expanding container.

1.32 Relation between Real and Apparent Expansion

Let:

- γ_r = coefficient of real expansion of liquid
- γ_a = coefficient of apparent expansion
- γ_v = coefficient of volume expansion of vessel

Then:

$$\gamma_a = \gamma_r - \gamma_v$$

Or:

$$\boxed{\gamma_r = \gamma_a + \gamma_v}$$

This relation is important for numerical problems.

1.33 Solved Example 3 — Linear Expansion

A metal rod of length **2 m** has coefficient of linear expansion: $\alpha = 1.2 \times 10^{-5}\ K^{-1}$
If its temperature increases by **100 K**, find the increase in length.
Using: $\Delta L = \alpha L_0 \Delta T$
Therefore: $\Delta L = (1.2 \times 10^{-5})(2)(100) = 2.4 \times 10^{-3}\ m$
Thus: $\Delta L = 2.4\ mm$
Answer: **Increase in length = 2.4 mm**

1.34 Solved Example 4 — Area Expansion

A metal sheet has area: $A_0 = 2\ m^2$ and coefficient of linear expansion: $\alpha = 1 \times 10^{-5}\ K^{-1}$
Its temperature increases by: $\Delta T = 50\ K$. Find the increase in area.
Using: $\Delta A = {}_{2\alpha A0 \Delta T}$
Therefore: $\Delta A = 2(1 \times 10^{-5})(2)(50) = 2 \times 10^{-3}\ m^2$
Answer: $\Delta A = 2 \times 10^{-3}\ m^2$

1.35 Solved Example 5 — Volume Expansion

A solid has volume: $V_0 = 1\ m^3$, and coefficient of volume expansion: $\gamma = 3 \times 10^{-5}\ K^{-1}$
If temperature increases by $\Delta T = 100\ K$. Find the increase in volume.
Using: $\Delta V = \gamma V_0 \Delta T$
Therefore: $\Delta V = (3 \times 10^{-5})(1)(100) = 3 \times 10^{-3}\ m^3$
Answer: $\Delta V = 3 \times 10^{-3}\ m^3$

1.36 Solved Example 6 — NEET/JEE Concept

A metal plate containing a circular hole is uniformly heated. What happens to the diameter of the hole?

Solution
Every linear dimension of the plate increases.
Therefore, the diameter of the hole also increases.
Answer: The diameter of the hole increases.

1.37 Solved Example 7 — Thermal Stress

A metal rod is heated through **100 K** and its expansion is completely prevented.
Given: $\mathbf{Y = 2 \times 10^{11}\ Pa,\ \alpha = 1 \times 10^{-5}\ K^{-1}}$
Find the thermal stress.
Using: **Thermal stress = YαΔT**
Therefore: $\mathbf{Stress = (2 \times 10^{11})\ (1 \times 10^{-5})(100) = 2 \times 10^{8}\ Pa}$
Answer: Thermal stress = 2×10^{8} Pa, compressive.

1.38 NEET/JEE Quick Insights

Insight 1: If a rod's temperature increases by ΔT: **ΔL = αLΔT**
Therefore, longer rods undergo greater absolute expansion for the same material and temperature change.

Insight 2: For isotropic solids: **β = 2α and γ = 3α**

Insight 3: If all dimensions of a cube increase by the same fractional amount, its volume increases approximately three times that fractional increase for small expansion.

Insight 4: A hole expands on heating because the entire material around it expands.

Insight 5: If expansion is completely prevented: **Thermal stress = YαΔT**

1.39 Quick Revision — Part 1

Concept	Important Result
Heat	Energy transferred due to temperature difference
Thermal equilibrium	No net heat transfer
Zeroth Law	Basis of temperature measurement
Celsius–Fahrenheit	C/5 = (F−32)/9
Celsius–Kelvin	K = C + 273.15
Linear expansion	ΔL = αLΔT
Area expansion	ΔA = βAΔT
Volume expansion	ΔV = γVΔT
Isotropic solid	β = 2α
Isotropic solid	γ = 3α
Thermal stress	YαΔT
Hole on heating	Expands
Real vs apparent expansion	$\boxed{\gamma_r = \gamma_a + \gamma_v}$

MASTER CONCEPT — PART 1

The main conceptual sequence is:

Temperature → Thermal Equilibrium → Zeroth Law → Temperature Scales → Thermal Expansion

The three most important expansion equations are:

$\Delta L = \alpha L \Delta T$

$\Delta A = \beta A \Delta T$

$\Delta V = \gamma V \Delta T$

For isotropic solids: **$\beta = 2\alpha$ and $\gamma = 3\alpha$**

And for a completely constrained heated rod: **Thermal stress = $Y\alpha\Delta T$**

PART 2: HEAT CAPACITY, SPECIFIC HEAT, CALORIMETRY AND CHANGE OF STATE

2.1 Heat and Temperature

When heat is supplied to a body, its temperature may increase, or the supplied energy may produce a change of state.
For example:

- Heating water from 20°C to 80°C → temperature increases.
- Heating water at 100°C → energy is used mainly for vaporisation while the temperature remains constant at atmospheric pressure.

Thus, heat supplied to a substance can produce:

1. Rise in temperature
2. Change of state
3. Sometimes both, depending on the process.

2.2 Heat Capacity

The **heat capacity** of a body is the amount of heat required to raise its temperature by one degree.
Mathematically,

$$\mathbf{C = Q/\Delta T}$$

Where:

- C = heat capacity
- Q = heat supplied
- ΔT = change in temperature

Therefore,

$$\mathbf{Q = C\Delta T}$$

SI Unit: J/K
Dimensions: $[C] = ML^2T^{-2}K^{-1}$

2.3 Physical Meaning of Heat Capacity

If a body has heat capacity: **C = 500 J/K** then 500 J of heat is required to raise its temperature by 1 K, provided its heat capacity remains approximately constant over that temperature range.

Important

Heat capacity is an **extensive property**.
It depends on the amount of substance present.
For example, two kilograms of a material generally have twice the heat capacity of one kilogram of the same material under the same conditions.

2.4 Specific Heat Capacity

The heat required to raise the temperature of **unit mass** of a substance by one degree is called its **specific heat capacity**.
It is represented by **s**.
Mathematically: **$s = Q/(m\Delta T)$**
Therefore: **$Q = ms\Delta T$**
Where:

- m = mass
- s = specific heat capacity
- ΔT = temperature change

SI Unit: J kg⁻¹ K⁻¹
Dimensions: [s] = $L^2T^{-2}K^{-1}$

2.5 Relation between Heat Capacity and Specific Heat

We know: **Q = CΔT and** Q **= msΔT**
Therefore: **C = ms**
Hence: **s = C/m**

Important

Heat capacity depends on mass.
Specific heat capacity is an intensive property and is independent of the amount of substance.

2.6 Water and Its High Specific Heat

Water has a relatively high specific heat capacity: **c (water) ≈ 4200 J kg⁻¹ K⁻¹**
This means a comparatively large amount of heat is required to raise the temperature of water.

Consequences

Water is used:

- As a coolant in automobile engines
- In industrial cooling systems
- In hot-water bottles
- For moderating temperature near large water bodies

2.7 Molar Heat Capacity

The heat required to raise the temperature of **one mole** of a substance by one kelvin is called its **molar heat capacity**.
It is represented by C_m
Therefore:

$$C_m = \frac{C}{n} = \frac{Q}{n\Delta T}$$

or

$$Q = nC_m\Delta T$$

Where n is the number of moles.
SI Unit: J mol⁻¹ K⁻¹

2.8 Heat Capacity, Specific Heat and Molar Heat Capacity

Quantity	Formula	SI Unit
Heat capacity	C = Q/ΔT	J/K
Specific heat	s = Q/(mΔT)	J kg^{-1} K^{-1}
Molar heat capacity	C_m = Q/(nΔT)	J mol^{-1} K^{-1}

2.9 Sensible Heat

The heat supplied to a substance that produces a change in temperature without changing its state is called **sensible heat**.

For constant specific heat: **Q = msΔT**

For example, heating water from 20°C to 50°C involves sensible heating.

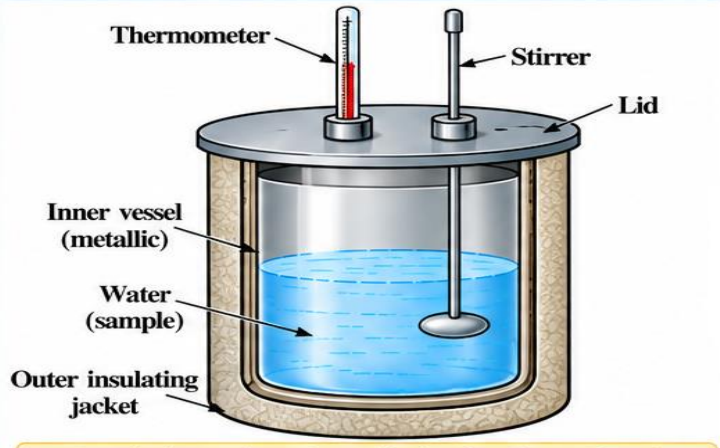
2.10 Calorimetry

Calorimetry is the measurement of heat exchanged during a physical or chemical process.

The device used for measuring heat exchange is called a **calorimeter**.

A calorimeter is designed to minimise heat exchange with the surroundings.

Figure 10.9: Basic Calorimeter



A calorimeter is a thermally insulated vessel used to measure the heat exchanged in a process.

2.11 Principle of Calorimetry

When hot and cold bodies are brought into thermal contact in an isolated system:

Heat lost by hot body = Heat gained by cold body

Thus: **Q (lost) = Q (gained)** or,

Total heat exchange = 0

This is based on the conservation of energy.

2.12 Derivation of Mixing Formula

Suppose:

- Hot body: mass m_1, specific heat s_1, initial temperature T_1
- Cold body: mass m_2, specific heat s_2, initial temperature T_2
- Final equilibrium temperature = T_f

Assume: $\mathbf{T_1 > T_f > T_2}$

Heat lost by hot body

$$Q_{lost} = m_1 s_1 (T_1 - T_f)$$

Heat gained by cold body

$$Q_{gained} = m_2 s_2 (T_f - T_2)$$

Using the principle of calorimetry:

$$m_1 s_1 (T_1 - T_f) = m_2 s_2 (T_f - T_1)$$

This is one of the most important calorimetry equations.

2.13 Water Equivalent of a Calorimeter

The **water equivalent** of a body is the mass of water that would have the same heat capacity as the body.

If:

- Heat capacity of calorimeter = C
- Specific heat of water = s_w

Then water equivalent W is: $\mathbf{W = C/s_w}$

Therefore, the calorimeter behaves thermally like W kilograms of water.

SI Unit: kg

2.14 Solved Example 1 — Heat Required

Find the heat required to raise the temperature of 2 kg of water from 20°C to 50°C.

Given: **m = 2 kg, s = 4200 J kg⁻¹ K⁻¹, ΔT = 50 − 20 = 30 K**

Using: **Q = msΔT**

Therefore: **Q = 2 × 4200 × 30 = 252000 J**

Answer: Q = 2.52 × 10^5 J

2.15 Solved Example 2 — Mixing of Water

100 g of water at 80°C is mixed with 200 g of water at 20°C. Find the final temperature, neglecting heat loss.

Since the substance is the same, its specific heat cancels.

Given: $m_1 = 100\ g,\ T_1 = 80^0C, m_2 = 200\ g, T_2 = 20^0C$

Using:

$$\boldsymbol{Q = ms\Delta t}$$

So, in equilibrium,

$$\boldsymbol{m_1 s(80 - T_f) = m_2 s(T_f - 20)}$$

Or

$$\boldsymbol{100 \times 80 - 100T_f = 200T_f - 4000}$$

$$\boldsymbol{T_f = 40^0C}$$

Answer: Final temperature = 40°C

2.16 Change of State

Matter can exist mainly in three states:

- Solid
- Liquid
- Gas

A substance can change from one state to another when heat is supplied or removed.

Important changes are:

Melting: Solid → Liquid

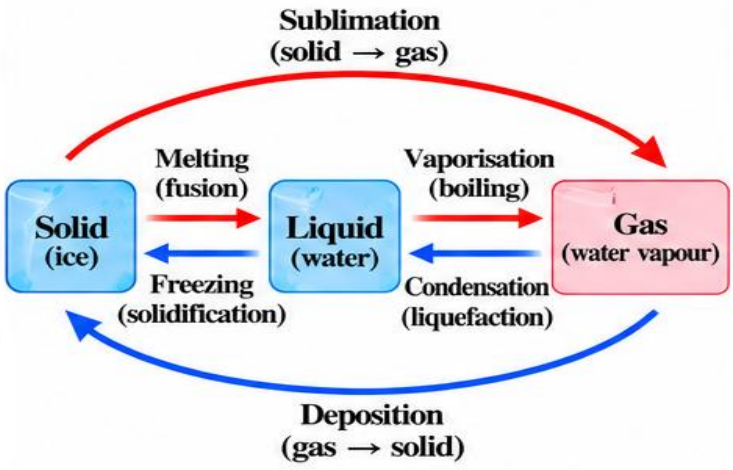
Freezing: Liquid → Solid

Vaporisation: Liquid → Gas

Condensation: Gas → Liquid

Sublimation: **Solid → Gas**
Deposition: **Gas → Solid**

Figure 10.10: Different Changes of State of Matter



2.17 Latent Heat

During a change of state, heat may be supplied without producing a change in temperature. This heat is called **latent heat**.

Definition

Latent heat is the heat required per unit mass of a substance to change its state at constant temperature.

The word "latent" means hidden

The heat supplied is used to change the internal structure and separation of particles rather than increasing the average kinetic energy responsible for temperature.

2.18 Specific Latent Heat

Specific latent heat is the heat required to change the state of **unit mass** of a substance at constant temperature.

It is represented by **L**.

Therefore: **Q = mL**

Where:

- Q = heat supplied
- m = mass
- L = specific latent heat

SI Unit: **J/kg**

2.19 Latent Heat of Fusion

The heat required to convert unit mass of a solid into liquid at its melting point is called the **specific latent heat of fusion**.

It is represented by $\mathbf{L_f}$

Therefore: $\mathbf{Q = mL_f}$

For ice at 0°C, approximately: $\mathbf{L_f \approx 3.34 \times 10^5\ J/kg}$

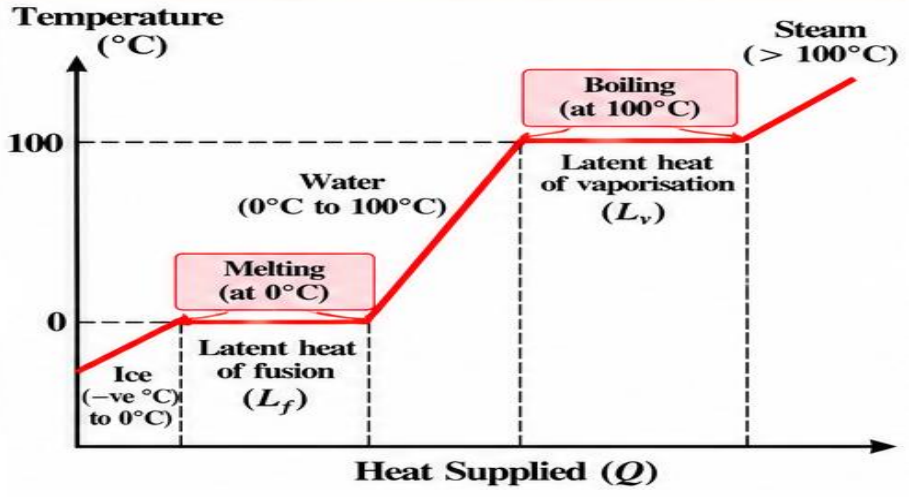
2.20 Latent Heat of Vaporisation

The heat required to convert unit mass of a liquid into vapour at its boiling point is called the **specific latent heat of vaporisation**.
It is represented by **Lv**.
Therefore: **Q = mLv**
For water at 100°C and standard atmospheric pressure, approximately: $\mathbf{Lv \approx 2.26 \times 10^6\ J/kg}$

2.21 Why Temperature Remains Constant During a Phase Change

Suppose ice at 0°C is being heated.
Initially: **Ice at 0°C → Water at 0°C**
The supplied heat does not increase the temperature.
Instead, it is used to overcome intermolecular forces and change the arrangement of molecules.
Similarly, when water boils at 100°C:
Water at 100°C → Steam at 100°C
The supplied heat is used primarily to separate molecules and produce the gaseous state.
Therefore:
Temperature remains constant during a phase change at constant pressure.

Figure 10.11: Heating Curve of Water



2.22 Heating Curve

The heating curve demonstrates three important facts:
Region 1: Temperature of solid increases
Region 2: Temperature remains constant during melting
Region 3: Temperature of liquid increases
Region 4: Temperature remains constant during boiling
Region 5: Temperature of vapour increases

2.23 Heat Required for Complete Heating Process

Suppose ice at 0°C is converted into steam at 100°C.
The process occurs in three stages:

Stage 1: Melting of ice: $Q_1 = mL_f$

Stage 2: Heating water from 0°C to 100°C: $Q_2 = ms_w\Delta T$

Stage 3: Vaporisation: $Q_3 = mLv$

Therefore,

$$Q_{total} = mL_f + ms_w\Delta T + mL_v$$

For ΔT = 100°C:

$$Q_{total} = mL_f + 100ms_w + mL_v$$

2.24 Cooling and Heating During Phase Changes

The same latent heat concepts apply in reverse.

Freezing: Liquid → Solid
Heat is released.

Condensation: Gas → Liquid
Heat is released.

Thus:

Melting ↔ Freezing
Vaporisation ↔ Condensation

The magnitude of latent heat involved is the same for the reverse process under corresponding conditions.

2.25 Solved Example 3 — Latent Heat of Fusion

How much heat is required to melt 0.5 kg of ice at 0°C?
Given: **m = 0.5 kg, $L_f = 3.34 \times 10^5$ J/kg**
Using: **$Q = mL_f$**
Therefore,
$Q = 0.5 \times 3.34 \times 10^5 = 1.67 \times 10^5$ J
Answer: $Q = 1.67 \times 10^5$ J

2.26 Solved Example 4 — Vaporisation

How much heat is required to convert 0.2 kg of water at 100°C into steam at 100°C?
Given: **m = 0.2 kg, Lv = 2.26×10^6 J/kg**
Using: **Q = mLv**
Therefore: **$Q = 0.2 \times 2.26 \times 10^6 = 4.52 \times 10^5$ J**
Answer: $Q = 4.52 \times 10^5$ J

2.27 Solved Example 5 — Ice to Water

How much heat is required to convert 1 kg of ice at 0°C into water at 20°C?
Two steps are required.

Step 1: Melt ice

$$Q_1 = mL_f$$

Step 2: Heat water from 0°C to 20°C

$$Q_2 = ms_w\Delta T$$

Therefore,

$$Q_{total} = Q_1 + Q_2 = mL_f + ms_w\Delta T$$

Substituting:

Q (total) = (1)(3.34 × 10⁵) + (1) (4200)(20) = 3.34 × 10⁵ + 8.4 × 10⁴ = 4.18 × 10⁵ J

Answer: Q (total) = 4.18 × 10⁵ J

2.28 Evaporation

Evaporation is the slow conversion of a liquid into vapour from its surface at temperatures below the boiling point.

It differs from boiling.

Evaporation

- Occurs at the surface
- Can occur at many temperatures
- Slow process
- Produces cooling

Boiling

- Occurs throughout the liquid
- Occurs at a definite boiling temperature for a given pressure
- Rapid process
- Vapour bubbles form throughout the liquid

2.29 Cooling Due to Evaporation

During evaporation, higher-energy molecules escape from the liquid surface.

The average kinetic energy of the remaining molecules decreases.

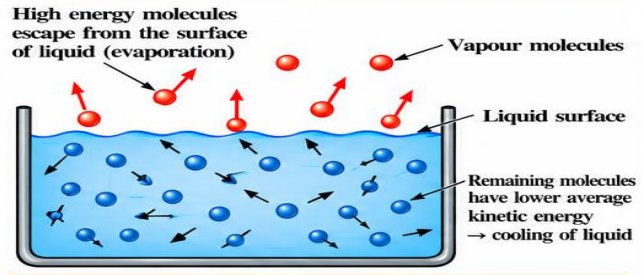
Therefore, the temperature of the remaining liquid falls.

This is called **evaporative cooling**.

Examples

- Sweating cools the body.
- Water kept in an earthen pot becomes relatively cool.
- Acetone or alcohol feels cool when applied to the skin.

Figure 10.12: Evaporation and Cooling



During evaporation, high energy molecules leave the surface, so the remaining molecules have lower average kinetic energy and the liquid cools.

2.30 Factors Affecting Evaporation

Evaporation increases with:

1. Increase in Surface Area

Greater surface area → greater evaporation

2. Increase in Temperature
Higher temperature → more molecules have sufficient energy to escape.

3. Increase in Wind Speed
Moving air removes vapour near the surface.
Therefore, evaporation increases.

4. Decrease in Humidity
Dry air can accept more water vapour.
Therefore, evaporation increases.

2.31 Evaporation vs Boiling

Evaporation	Boiling
Surface phenomenon	Bulk phenomenon
Can occur at any temperature	Occurs at boiling point for given pressure
Slow	Rapid
Produces cooling	During boiling at constant pressure, the temperature of the liquid remains constant while the phase change takes place.
No bubbles throughout liquid	Vapour bubbles form throughout liquid

---

2.32 Vapour Pressure
When a liquid is kept in a closed container, some molecules escape from its surface and form vapour.
At the same time, some vapour molecules return to the liquid.
Eventually, a dynamic equilibrium may be established.
The pressure exerted by the vapour in equilibrium with its liquid is called **vapour pressure**.

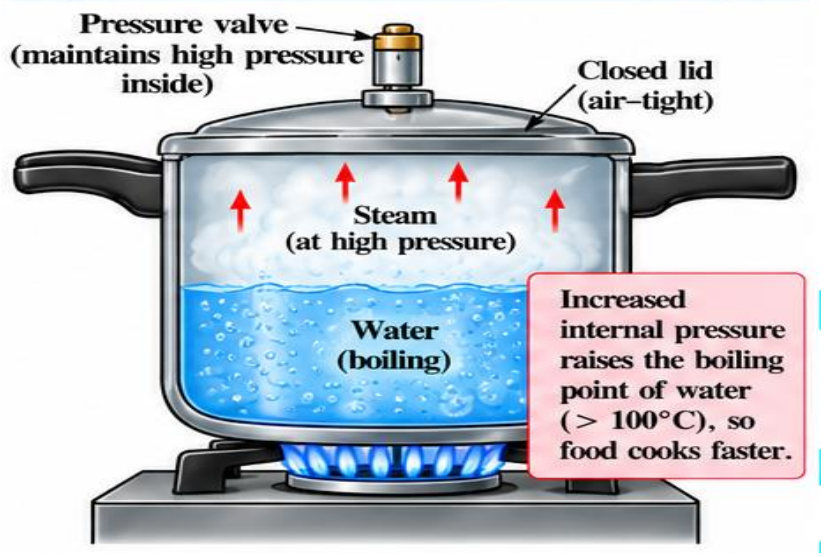
Important
Vapour pressure increases with temperature.

2.33 Boiling Point
A liquid boils when its vapour pressure becomes equal to the external pressure acting on the liquid.
Thus:
Boiling condition: Vapour pressure = External pressure

Consequences:
If external pressure decreases, **Boiling point decreases**
If external pressure increases, **Boiling point increases**

2.34 Pressure Cooker
A pressure cooker works on the principle that increasing pressure raises the boiling point of water.
Inside a pressure cooker: **Pressure ↑ → Boiling point ↑**
Therefore, food can be cooked at a temperature higher than 100°C under typical conditions.
This reduces cooking time.

Figure 10.13: Pressure Cooker Principle



2.35 Boiling at High Altitudes

At high altitude: **Atmospheric pressure ↓**
Therefore: **Boiling point ↓**
Water may boil below 100°C.
Consequently, cooking can take longer because the cooking temperature is lower.

2.36 NEET/JEE Quick Insights

Insight 1

During a phase change: **Temperature remains constant** provided the pressure remains constant and the phase change is occurring under equilibrium conditions.

Insight 2

Heat required to raise temperature: **$Q = msΔT$**
Heat required for phase change: **$Q = mL$**

Insight 3

For the same mass: Greater specific heat → greater heat required for the same temperature rise.

Insight 4

At boiling: **Pvapour = Pexternal**

Insight 5

Higher atmospheric pressure: **Boiling point ↑**
Lower atmospheric pressure: **Boiling point ↓**

Insight 6

Evaporation causes cooling because preferentially higher-energy molecules escape from the liquid surface.

MASTER CONCEPT — PART 2

The central idea of this Part is:

Heat supplied → Temperature change OR Change of state

For temperature change: **$Q = ms\Delta T$**

For change of state: **$Q = mL$**

And for calorimetry: **Heat lost = Heat gained**

The most important conceptual distinction is:

During a phase change, heat is supplied or removed while the temperature remains constant; the energy is associated primarily with changing the molecular arrangement and intermolecular separation.

PART 3: HEAT TRANSFER, THERMAL CONDUCTIVITY, RADIATION AND NEWTON'S LAW OF COOLING

3.1 Modes of Heat Transfer

Heat can be transferred from one region to another by three main mechanisms:

1. **Conduction**
2. **Convection**
3. **Radiation**

These mechanisms differ in the way thermal energy is transported.

3.2 Conduction

Conduction is the mode of heat transfer in which thermal energy is transferred from the hotter region to the colder region through a material medium without bulk motion of the material as a whole.

It is most important in solids.

Microscopic Explanation

In a solid:

- Atoms and molecules vibrate about their mean positions.
- Hotter particles have greater vibrational energy.
- They transfer energy to neighbouring particles.
- Energy therefore moves from the hotter region towards the colder region.

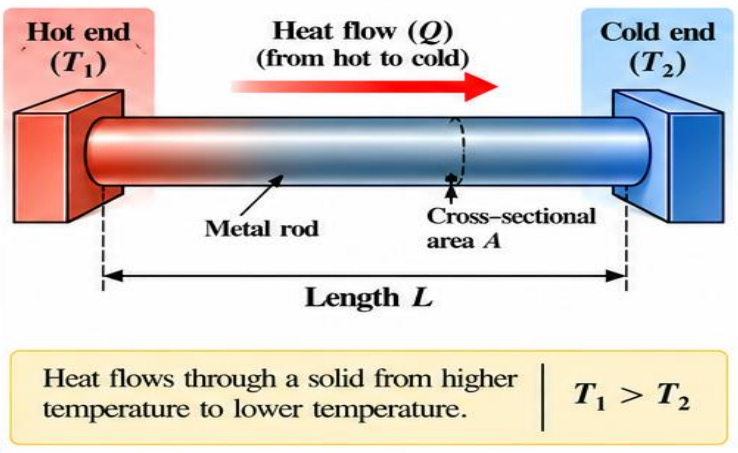
Important

In conduction:

Matter does not undergo bulk flow.

Only thermal energy is transferred.

Figure 10.14: Heat Transfer by Conduction



Heat flows through a solid from higher temperature to lower temperature. | $T_1 > T_2$

3.3 Thermal Conductivity

Different materials conduct heat at different rates.

The ability of a material to conduct heat is measured by its **thermal conductivity**.

It is represented by **k**.

Consider a slab of:

- Area = A
- Thickness = L
- Temperature difference = ΔT

The rate of heat conduction is:

$$\mathbf{dQ/dt = kA\Delta T/L}$$

For a temperature gradient:

$$\mathbf{dQ/dt = -kA(dT/dx)}$$

The negative sign indicates that heat flows towards decreasing temperature.

3.4 Definition of Thermal Conductivity

Thermal conductivity is defined as:
The amount of heat flowing per second through a unit area of a material of unit thickness when the temperature difference between its opposite faces is one kelvin.
From:
$\mathbf{dQ/dt = kA\Delta T/L}$
For: $\mathbf{A = 1\ m^2, L = 1\ m, \Delta T = 1\ K}$
We get:
$\mathbf{k = dQ/dt}$

3.5 SI Unit of Thermal Conductivity

From: $\mathbf{k = (dQ/dt)L/(A\Delta T)}$
SI unit: $\mathbf{W\ m^{-1}\ K^{-1}}$
Dimensions: $\mathbf{[k] = MLT^{-3}K^{-1}}$

3.6 Good and Poor Conductors

Good Conductors

They have relatively high thermal conductivity.
Examples: Copper , Aluminium, Silver, Iron

Poor Conductors / Thermal Insulators

They have relatively low thermal conductivity.
Examples: Wood, Glass, Rubber, Air, Wool

3.7 Thermal Resistance

Thermal resistance measures the opposition offered by a material to heat flow.
For a slab: $\mathbf{R_{th} = L/(kA)}$
Therefore,

$$\mathbf{dQ/dt = \Delta T/R_{th}}$$

This is analogous to Ohm's law: $\mathbf{I = V/R}$
Where:

- Temperature difference ΔT corresponds to potential difference.
- Heat-flow rate corresponds to electric current.
- Thermal resistance corresponds to electrical resistance.

3.8 Composite Slabs

When different materials are arranged one after another in the direction of heat flow, they are in **series**.
For two slabs: $\mathbf{R_1 = L_1/(k_1A)\ ,\ R_2 = L_2/(k_2A)}$
Total thermal resistance: $\mathbf{R\ (total) = R_1 + R_2}$

Therefore: **$R\ (total) = L_1/(k_1A) + L_2/(k_2A)$**
Heat-flow rate: **$dQ/dt = \Delta T/R\ (total)$**

3.9 Slabs in Parallel

If different materials provide separate paths for heat flow between the same two temperatures, they are effectively in **parallel**.
For parallel paths: H**eat-flow rates add**
Therefore,

$$H\ (total) = H_1 + H_2 + ...$$

This concept is useful in composite walls and thermal insulation problems.

3.10 Temperature Gradient

The temperature gradient is the rate of change of temperature with distance.
It is written as: **dT/dx**
For one-dimensional steady conduction: **$H = -kA(dT/dx)$**
Where, H denotes heat transferred per unit time.

Important: The negative sign indicates that heat flows from higher temperature to lower temperature.

3.11 Steady-State Heat Conduction

A rod is said to be in **steady-state thermal conduction** when the temperature at each point remains constant with time, although heat continues to flow.
For a uniform rod: **$H = kA(T_1 - T_2)/L$**
Where:

- H = heat transferred per unit time
- T_1 = temperature of hot end
- T_2 = temperature of cold end
- A = cross-sectional area
- L = length

3.12 Solved Example 1 — Thermal Conduction

A metal slab has: **$k = 200\ W\ m^{-1}\ K^{-1}$, $A = 0.01\ m^2$, $L = 0.1\ m$** and temperature difference: **$\Delta T = 50\ K$.** Find the rate of heat conduction.
Using: **$H = kA\Delta T/L$**
Therefore,

$$H = (200)(0.01)(50)/(0.1) = 1000\ W$$

Answer: Heat-flow rate = 1000 W

3.13 Convection

Convection is the mode of heat transfer in which thermal energy is carried from one region to another by the bulk motion of a fluid.
Convection occurs in:

- Liquids
- Gases

It does not occur in the same bulk-flow manner in solids.

3.14 Types of Convection

There are two main types:

1. Natural or Free Convection

Fluid motion occurs due to density differences produced by temperature differences.
Example:

- Heating of water in a vessel
- Warm air rising
- Sea breeze
- Land breeze

2. Forced Convection

Fluid motion is produced by an external device.
Examples: Fan, Pump, Air conditioner, Forced-air cooling system

---

3.15 Convection in the Atmosphere

Convection plays an important role in atmospheric processes.
When air is heated:
Temperature ↑ → Density ↓
The warmer air rises.
Cooler, denser air moves downward.
This produces convection currents.
These currents contribute to:

- Cloud formation
- Atmospheric circulation
- Wind systems
- Weather processes

3.16 Sea Breeze

During the daytime:

- Land heats faster than water.
- Air above land becomes hotter.
- Hot air rises.
- Cooler air from the sea moves towards the land.

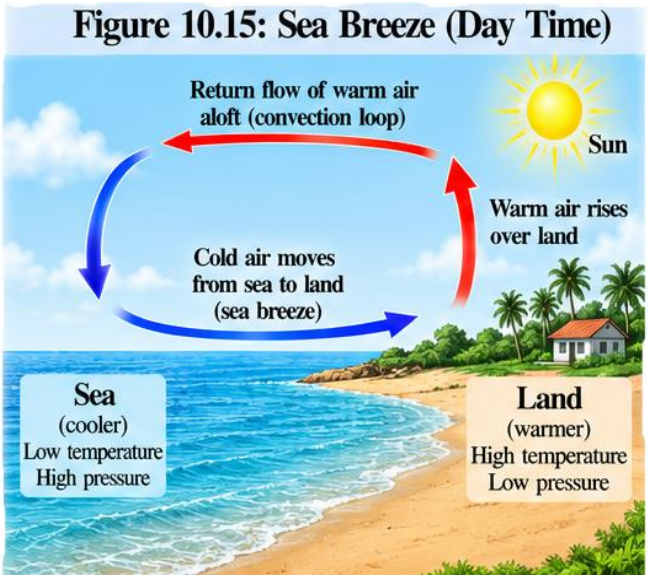
This is called **sea breeze**.

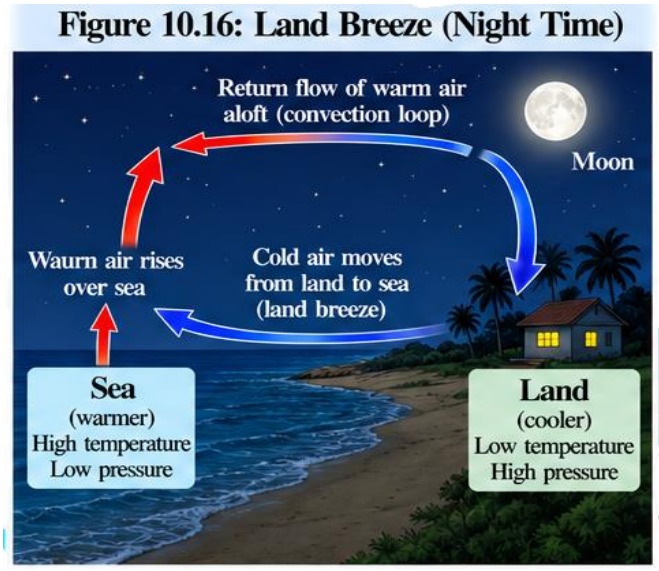
3.17 Land Breeze

At night:

- Land cools faster than water.
- Air above the sea remains relatively warmer.
- Warm air rises over the sea.
- Cooler air moves from land towards the sea.

This is called **land breeze**.





3.18 Radiation

Radiation is the mode of heat transfer in which thermal energy is transferred through electromagnetic waves without requiring a material medium.

Therefore:

Radiation can occur through vacuum.

This is how energy from the Sun reaches Earth.

3.19 Thermal Radiation

All bodies above absolute zero emit electromagnetic radiation because of their thermal motion. This radiation is called **thermal radiation**.

The nature and intensity of emitted radiation depend on:

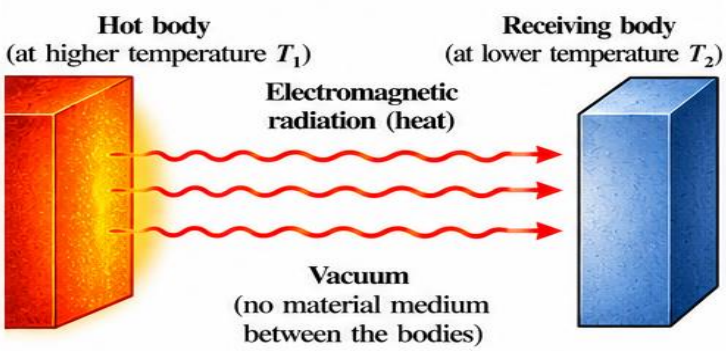
- Temperature
- Surface properties
- Wavelength

3.20 Important Properties of Thermal Radiation

Thermal radiation:

1. Does not require a material medium.
2. Can travel through vacuum.
3. Travels at the speed of light in vacuum.
4. Can be absorbed, reflected or transmitted.
5. Depends strongly on temperature.

Figure 10.17: Heat Transfer by Radiation



Heat is transferred from a hotter body to a colder body by electromagnetic radiation. No material medium is required.

3.21 Absorptive, Reflective and Transmissive Properties

When radiation falls on a body, it can be:

- Absorbed
- Reflected
- Transmitted

If the incident energy is Q:

Q = Q (absorbed) + Q (reflected) + Q (transmitted)

For opaque bodies: **Q (transmitted) = 0**

Therefore: **Q = Q (absorbed) + Q (reflected)**

3.22 Good Absorbers and Good Emitters

A surface that is a good absorber of thermal radiation is generally also a good emitter.

Examples

- Black, rough surfaces → good absorbers and emitters.
- Shiny, polished surfaces → poor absorbers and emitters.

This principle is used in:

- Solar collectors
- Thermos flasks
- Radiators
- Thermal shields

3.23 Blackbody

A **blackbody** is an ideal body that absorbs all incident electromagnetic radiation, irrespective of wavelength and direction.

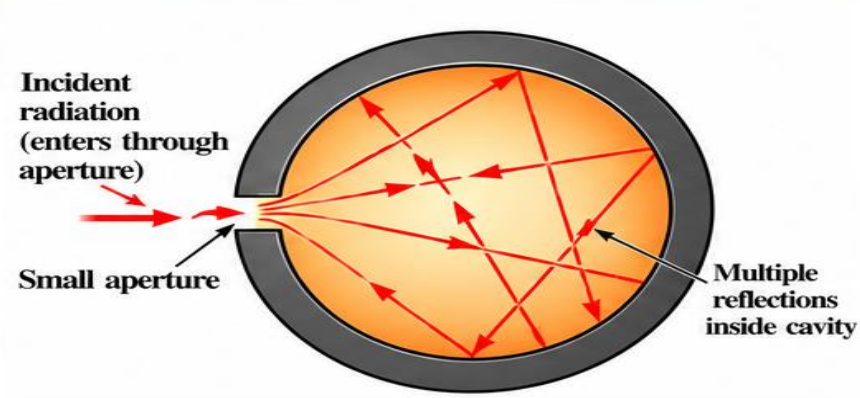
Therefore, absorptivity: **a = 1**

A blackbody is also an ideal emitter.

Important

A blackbody is an idealised concept. No ordinary object is a perfect blackbody over all wavelengths.

Figure 10.18: Ideal Black Body



A hollow cavity with a small aperture absorbs almost all the incident radiation. Very little radiation escapes from the cavity. It behaves as an ideal black body.

3.24 Stefan–Boltzmann Law

The total radiant energy emitted per unit time by a blackbody is proportional to the fourth power of its absolute temperature.

Therefore: $\mathbf{P = \sigma A T^4}$

Where:

- P = power radiated
- A = surface area
- T = absolute temperature
- σ = Stefan–Boltzmann constant

Its value is approximately: $\mathbf{\sigma = 5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}}$

3.25 Stefan–Boltzmann Law for a Real Body

A real body is not a perfect blackbody.

For a real surface: $\mathbf{P = \varepsilon \sigma A T^4}$

Where: ε is the emissivity.

For a perfect blackbody: $\mathbf{\varepsilon = 1}$

Therefore: $\mathbf{P\ (blackbody) = \sigma A T^4}$

3.26 Net Radiation Exchange

If a body at temperature T is surrounded by an environment at temperature T_0, the net power radiated is approximately:

$\mathbf{P_{net} = \varepsilon \sigma A (T^4 - T_0^4)}$

This expression is important in radiation and cooling problems.

Important: Temperatures in this equation must be expressed in **kelvin**.

3.27 Wien's Displacement Law

The wavelength corresponding to maximum intensity of radiation emitted by a blackbody is related to its absolute temperature by: $\mathbf{\lambda_{max} T = b}$ where b is Wien's displacement constant.

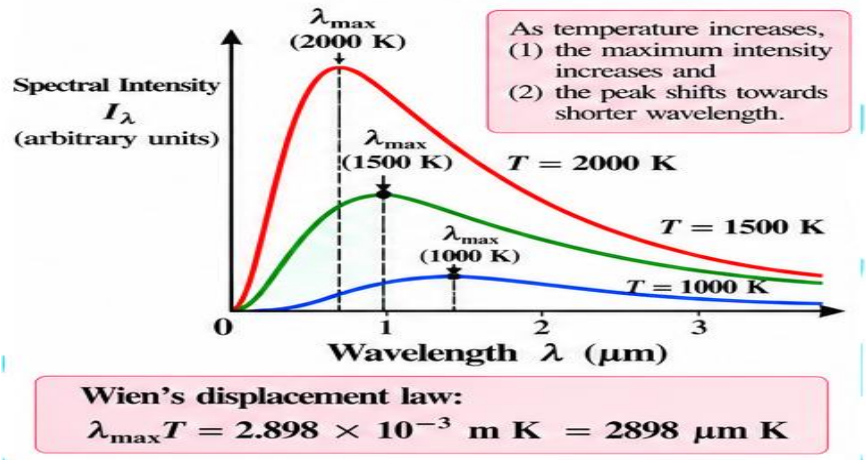
Approximately: $\mathbf{b = 2.898 \times 10^{-3}\ m \cdot K}$

Therefore: **λmax = b/T**

Important: As temperature increases: **λmax decreases**

Thus, hotter objects emit their maximum radiation at shorter wavelengths.

Figure 10.19: Black Body Radiation Spectrum and Wien's Displacement Law



3.28 Applications of Wien's Law

Wien's law is useful for estimating the temperature of:

- Stars
- Hot objects
- Thermal sources

For example, the colour of a hot object changes as its temperature increases.

3.29 Newton's Law of Cooling

Newton's law of cooling states that:

The rate of loss of heat of a body is approximately proportional to the temperature difference between the body and its surroundings, provided the temperature difference is not very large.

Mathematically:

$$-dQ/dt \propto (T - T_s)$$

Therefore:

$$-dQ/dt = h\,(T - T_s)$$

Where:

- T = temperature of the body
- Ts = temperature of surroundings
- h = proportionality constant

3.30 Temperature-Time Relation in Newton's cooling

For a body of heat capacity C:

$$dQ = C\,dT$$

Therefore:

$$-C(dT/dt) = h\,(T - Ts)$$

Or,

$$dT/dt = -(h/C)(T - Ts)$$

Integrating:

$$T - T_S = (T_0 - T_S)e^{-ht/C}$$

Where:

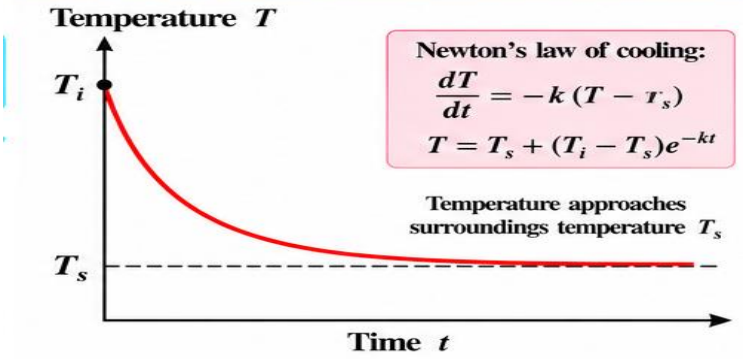
- T_0 **= Initial temperature of body**
- T_S **= Surrounding temperature**

For k = h/C, we have

$$T - T_S = (T_0 - T_S)e^{-kt}$$

This shows that the temperature difference decreases approximately exponentially with time under the conditions of Newton's law.

Figure 10.20: Newton's Cooling Curve



A hot body cools rapidly at first, and then more slowly, and finally approaches the temperature of the surroundings T_s.

Note:

If a body is cooled from temperature θ_1 to θ_2 in time t having surrounding temperature θ_s , then the important relation is given as below:

$$\frac{\theta_1 - \theta_2}{t} = k\left(\frac{\theta_1 + \theta_2}{2} - \theta_s\right)$$

Where, k = constant

3.31 Physical Meaning of Newton's Cooling Law

At the beginning: **T − Ts is large**
Therefore: **Rate of cooling is large.**
Later: **T − Ts decreases**
Therefore: **Rate of cooling decreases.**
Finally, when: **T = Ts** the net cooling rate becomes zero.

3.32 Conditions for Newton's Law of Cooling

Newton's law of cooling is approximately valid when:

- Temperature difference is not very large.
- Surface properties remain approximately unchanged.

- Conditions surrounding the body remain reasonably constant.
- Heat loss occurs under approximately steady conditions.
- The temperature of the surroundings is assumed to remain approximately constant.

3.33 Solved Example 2 — Stefan–Boltzmann Law

A blackbody of area **2 m^2** is maintained at temperature **1000 K**. Find the power radiated.
Using: **$P = \sigma A T^4$**
Therefore: **$P = (5.67 \times 10^{-8})(2)(1000)^4 = 5.67 \times 10^{-8} \times 2 \times 10^{12} = 1.134 \times 10^5$ W**
Answer: $P \approx 1.13 \times 10^5$ W

3.34 Solved Example 3 — Wien's Law

A blackbody has its maximum emission at: **$\lambda_{max} = 5 \times 10^{-7}$ m.** Find its approximate temperature.
Using: **$\lambda_{max} T = 2.898 \times 10^{-3}$ m·K**
Therefore: **$T = (2.898 \times 10^{-3})/(5 \times 10^{-7}) \approx 5796$ K**
Answer: T ≈ 5800 K

3.35 Solved Example 4 — Thermal Conductivity

A rod has: **$k = 100$ W m^{-1} K^{-1}, $A = 0.02$ m^2, $L = 0.5$ m** and temperature difference: **$\Delta T = 20$ K**
Find the rate of heat conduction.
Using: **$H = kA\Delta T/L$**
Therefore: **$H = (100)(0.02)(20)/(0.5) = 80$ W**
Answer: H = 80 W

3.36 Solved Example 5 — Newton's Cooling Concept

Two identical bodies are initially at different temperatures but placed in the same surroundings. The hotter body cools faster initially.

Reason

According to Newton's law: **Rate of cooling $\propto (T - T_s)$**
The hotter body has a larger temperature difference from the surroundings.
Therefore, its initial rate of cooling is greater.

3.37 Important Comparison of Heat Transfer Modes

Property	Conduction	Convection	Radiation
Medium required	Yes	Yes	No
Bulk movement of matter	No	Yes	No
Important in	Solids	Fluids	All bodies above absolute zero
Vacuum possible?	No	No	Yes
Example	Metal rod	Boiling water	Sunlight

3.38 NEET/JEE Quick Insights

Insight 1: For blackbody radiation: **$P \propto T^4$**
If absolute temperature becomes twice: **$P' = 16P$**

Insight 2: From Wien's law: **$\lambda_{max} \propto 1/T$**
If temperature doubles: **λ_{max} becomes half.**

Insight 3: For a slab: **$H = kA\Delta T/L$**
Therefore:
$H \propto A$
$H \propto \Delta T$
$H \propto k$
$H \propto 1/L$

Insight 4: If the thickness of a conducting slab doubles whiles all other quantities remain constant:
Heat-flow rate becomes half.

Insight 5: For thermal resistance: **$R_{th} = L/(kA)$**
Thus: **$H = \Delta T/R_{th}$**

3.39 Quick Revision — Part 3

Concept	Key Result
Conduction	Energy transfer without bulk motion
Convection	Energy transfer by bulk fluid motion
Radiation	Electromagnetic energy transfer
Thermal conductivity	k
Conduction rate	$H = kA\Delta T/L$
Thermal resistance	$R_{th} = L/(kA)$
Blackbody	Perfect absorber and ideal emitter
Stefan–Boltzmann law	$P = \sigma AT^4$
Real body	$P = \varepsilon\sigma AT^4$
Wien's law	$\lambda_{max}T = b$
Newton cooling	Rate $\propto$ temperature difference

One-line conceptual summary:

Conduction transfers thermal energy through a medium without bulk motion, convection transfers energy through bulk motion of a fluid, and radiation transfers energy through electromagnetic waves and can occur even through vacuum.

PART 4: ANOMALOUS EXPANSION OF WATER, THERMAL EXPANSION APPLICATIONS AND ADVANCED CONCEPTS

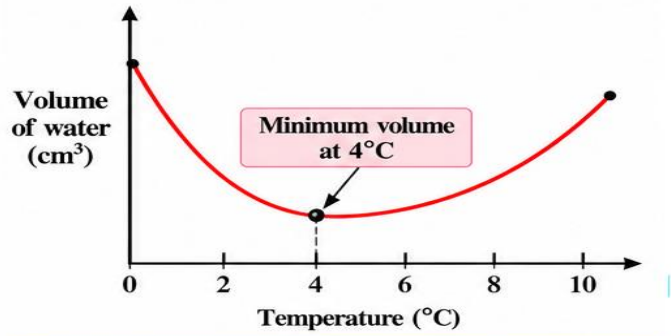
4.1 Anomalous Expansion of Water

Most liquids expand when heated and contract when cooled.
Water behaves differently over the temperature range from **0°C to 4°C**.
This unusual behaviour is called the **anomalous expansion of water**.

Important Observation

When water is heated from: **0°C → 4°C** its volume **decreases**.
Therefore, its density **increases**.
At: **4°C,** water has approximately: **Maximum density** and **Minimum volume**
When water is heated above 4°C: **Temperature ↑ → Volume ↑** and **Density ↓**

Figure 10.21: Anomalous Expansion of Water



The volume of water decreases from 0°C to 4°C, becomes minimum at 4°C and then increases on further heating. This is called the anomalous expansion of water.

4.2 Density–Temperature Relationship of Water

Since: **ρ = m/V** and mass remains constant,

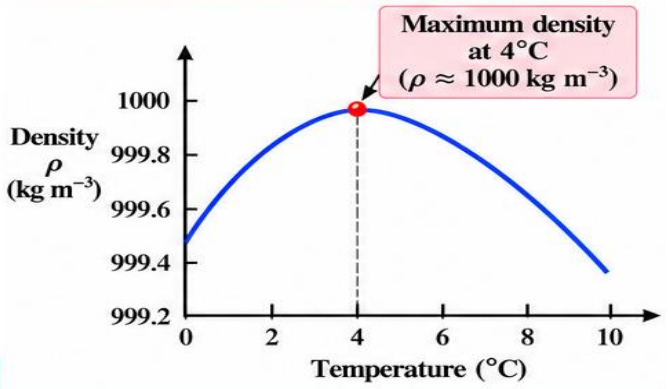
Density ∝ 1/Volume

Therefore:

- At 4°C → volume is minimum
- Hence density is maximum.

The density of water is approximately:
1000 kg/m³ at 4°C

Figure 10.22: Density of Water versus Temperature



The density of water increases from 0°C to 4°C, becomes maximum at 4°C, and then decreases on further heating.

4.3 Why Anomalous Expansion of Water is Important

The anomalous expansion of water has major consequences for aquatic life in cold regions.
Consider a lake during winter.
When the atmospheric temperature falls:

Stage 1

Water near the surface cools
When it reaches: **4°C,** it becomes denser and sinks.

Stage 2

Further cooling of surface water below 4°C makes it **less dense**.
Therefore, the colder water remains near the surface.

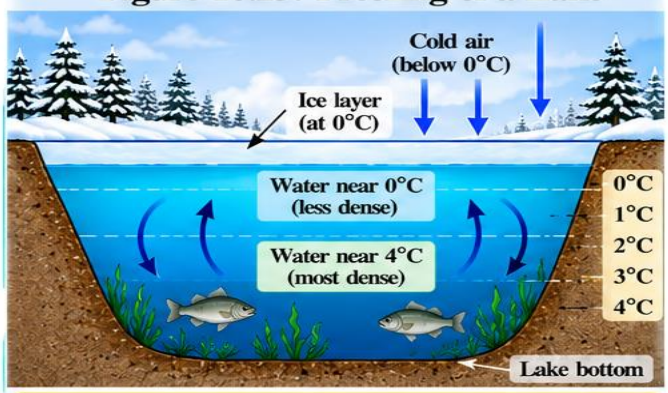
Stage 3

Eventually, the surface may reach 0°C and freeze.
Ice forms at the top.

Stage 4

The deeper water remains near 4°C.
Thus, aquatic organisms can survive beneath the ice.

Figure 10.23: Freezing of a Lake



In winter, water at 4°C (maximum density) remains at the bottom of the lake, while water at 0°C stays on top and freezes. This allows aquatic life to survive.

4.4 Detailed Explanation of Lake Freezing

Suppose the surface temperature initially falls from 10°C towards 4°C.
Water at the surface becomes denser and sinks.
Warmer water from below rises.
This produces convection currents.
When the surface temperature falls below 4°C:
Density decreases
Therefore, the colder surface water remains at the top.
Convection gradually stops.
The surface eventually reaches 0°C and freezes.
The ice layer acts as a thermal insulator.
Therefore, the water below does not easily freeze.

4.5 Why Ice Floats on Water

Ice is less dense than liquid water.
Approximately: **Density of ice ≈ 917 kg/m³** while: **Density of water ≈ 1000 kg/m³**
Therefore: **ρ ice < ρ water**
Hence ice floats

Important Concept

The anomalous expansion of water is related to the molecular structure of hydrogen-bonded water.

4.6 Important Numerical Concept

If the container expands appreciably:
Apparent expansion < Real expansion
because part of the real expansion is occupied by the expansion of the container itself.

4.7 Thermal Expansion of a Liquid in a Solid Vessel

Suppose a liquid is contained in a vessel.
If: $\gamma_r > \gamma_v$ then: $\gamma_a > 0$
The liquid level rises on heating.
If: $\gamma_r = \gamma_v$ then: $\gamma_a = 0$
The liquid level does not change.
If: $\gamma_r < \gamma_v$ then: $\gamma_a < 0$
The liquid level may fall.

4.8 Thermal Stress Due to Constrained Expansion

Consider a rod of length L that is heated by ΔT.
If it is free to expand: $\Delta L = \alpha L \Delta T$
No thermal stress develops.
If the rod is completely constrained: $\Delta L = 0$
The thermal expansion is prevented.
An internal restoring force develops.
The resulting stress is:
Thermal stress:

$$|\sigma| = Y\alpha|\Delta T|$$

- Heating under complete constraint → Compressive stress.
- Cooling under complete constraint → Tensile stress.

Where: Y is Young's modulus.

4.9 Thermal Expansion in Bridges

Long bridges are constructed with expansion joints.
When temperature increases:
Bridge length increases
If no provision is made for expansion, large thermal stresses can develop.
Expansion joints allow controlled expansion and contraction.

4.10 Thermal Expansion in Railway Tracks

Railway tracks are exposed to large temperature changes.
If rails were placed without expansion gaps:
Temperature ↑ → Rail expands → Compressive stress develops
This may cause bending or deformation.
Therefore, appropriate expansion arrangements are provided.

4.11 Thermal Expansion in Pipelines

Long pipelines carrying:

- Water
- Oil
- Steam
- Gas

may undergo significant thermal expansion.
Flexible joints or bends are provided to accommodate this expansion.

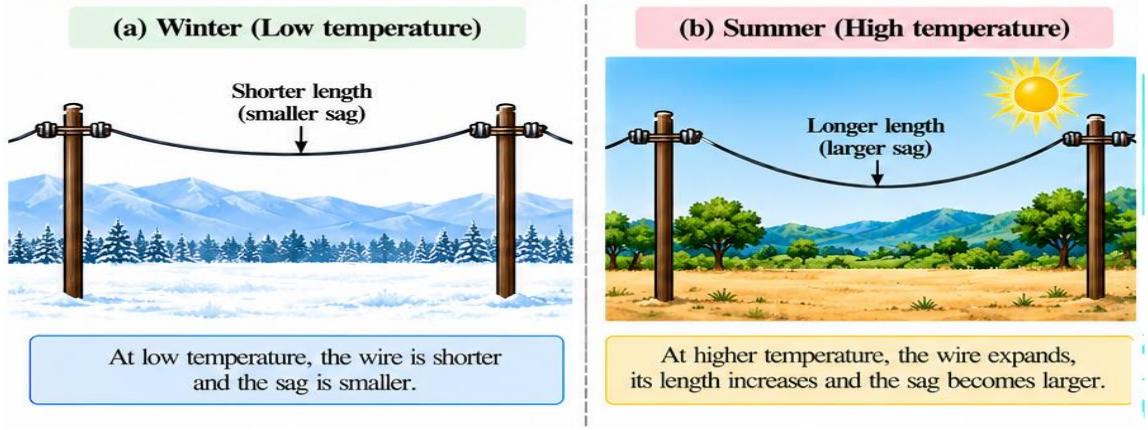
4.12 Thermal Expansion of Electric Wires

Overhead electric wires expand during hot weather and contract during cold weather.
Therefore, wires are not installed perfectly tight.
Some sag is intentionally allowed.

Important

In winter:
Temperature ↓ → Wire contracts → Sag decreases
In summer:
Temperature ↑ → Wire expands → Sag increases

Figure 10.24: Thermal Expansion of an Overhead Wire



4.13 Bimetallic Strip — Detailed Application

Consider two metals A and B having: $\alpha_A > \alpha_B$
When heated, metal A tends to expand more.
Since the two metals are bonded together, they cannot expand independently.
The strip bends.
The metal with the larger coefficient of expansion lies on the **outer side of the bend** when the strip is heated.

Applications

- Thermostat
- Electric iron
- Automatic temperature switch
- Fire alarm
- Temperature-controlled circuits

4.14 Thermal Insulation

Thermal insulation reduces unwanted heat transfer.
Good thermal insulators have low thermal conductivity.
Examples:

- Wool
- Fiberglass
- Thermocol
- Foam

- Air
- Vacuum

Why Wool Keeps Us Warm

Wool fibres trap air.
Air is a poor conductor of heat.
Therefore, trapped air reduces heat transfer from the body to the surroundings.

4.15 Thermos Flask

A thermos flask is designed to minimise heat transfer by:

- Conduction
- Convection
- Radiation

Construction

It generally contains:

1. Double-walled container
2. Vacuum between walls
3. Silvered or reflective surfaces
4. Insulating stopper

Role of Vacuum

Vacuum reduces:

- Conduction
- Convection

Vacuum reduces conduction and convection, while the reflective surfaces reduce radiative heat transfer.

Role of Shiny Surface

The reflective surface reduces radiant heat transfer.

4.16 Why Metal Feels Colder Than Wood

Suppose metal and wood are kept in the same room for a long time.
Both are approximately at the same temperature.
Yet metal feels colder.

Reason

Metal has much higher thermal conductivity than wood.
When the hand touches metal:
Heat flows rapidly from hand → metal
Therefore, the hand loses thermal energy quickly.
Wood transfers heat much more slowly.
Thus, metal feels colder even though both objects may have the same temperature.

4.17 Why Clothes Keep Us Warm

Clothes, especially woolen clothes, reduce heat loss from the body.
They trap air and reduce conduction.
Multiple layers are especially effective because they trap additional air pockets.
Thus:
More trapped air → Better thermal insulation

4.18 Why White Clothes Are Preferred in Summer

White and light-coloured surfaces generally reflect a larger fraction of incident solar radiation than dark surfaces.
Therefore, they absorb less radiant energy.
Hence, light-coloured clothing is generally more comfortable in strong sunlight.
Dark surfaces generally absorb more radiation.

4.19 Why Black Surfaces are Used in Solar Absorbers

A black or selectively absorbing surface can absorb a large fraction of incident solar radiation.
Therefore, dark surfaces are useful in:

- Solar water heaters
- Solar cookers
- Solar thermal collectors

However, actual engineering surfaces may be specially designed coatings rather than ordinary black paint.

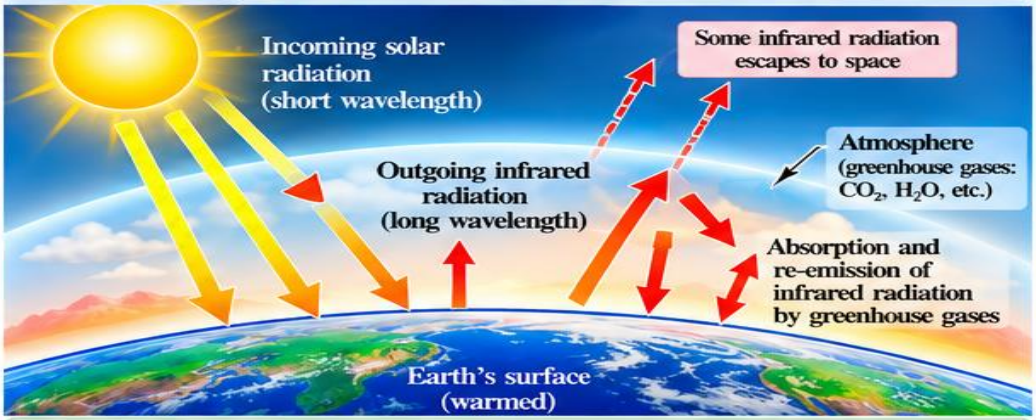
4.20 Greenhouse Effect — Basic Physics

The Earth receives solar radiation mainly at relatively shorter wavelengths.
The Earth's surface absorbs part of this energy and emits thermal radiation at longer wavelengths.
Certain atmospheric gases absorb and re-emit some of this outgoing infrared radiation.
This contributes to warming of the lower atmosphere and Earth's surface.
This phenomenon is commonly called the **greenhouse effect**.

Important

The greenhouse effect is a natural physical phenomenon. Human activities can alter atmospheric concentrations of greenhouse gases and thereby influence the Earth's energy balance.

Figure 10.25: Basic Greenhouse Effect



The atmosphere is nearly transparent to incoming solar radiation but absorbs and re-emits the outgoing infrared radiation, keeping the Earth's surface warmer. This is called the greenhouse effect.

4.21 Solved Example 1 — Anomalous Expansion

At which temperature does water have approximately maximum density under ordinary atmospheric conditions?

Answer: 4°C

At approximately 4°C: **Volume of water is minimum** and therefore: **Density is maximum.**

4.22 Solved Example 2 — Apparent Expansion

A liquid has coefficient of real expansion: $\gamma_r = 8 \times 10^{-4}\ K^{-1}$

The container has coefficient of volume expansion: $\gamma_v = 2 \times 10^{-4}\ K^{-1}$

Find the apparent coefficient of expansion.

Using: $\gamma_a = \gamma_r - \gamma_v$

Therefore: $\gamma_a = 8 \times 10^{-4} - 2 \times 10^{-4} = 6 \times 10^{-4}\ K^{-1}$

Answer : $\gamma_a = 6 \times 10^{-4}\ K^{-1}$

4.23 Solved Example 3 — Thermal Stress

A steel rod has: $Y = 2 \times 10^{11}$ Pa, $\alpha = 1.2 \times 10^{-5}\ K^{-1}$

It is heated by: $\Delta T = 50$ K and its expansion is completely prevented. Find the thermal stress.

Using: **Stress = $Y\alpha\Delta T$**

Therefore: **Stress = $(2 \times 10^{11})(1.2 \times 10^{-5})(50) = 1.2 \times 10^{8}$ Pa**

Answer: Thermal stress = 1.2×10^{8} Pa, compressive.

4.24 Solved Example 4 — Stefan–Boltzmann Concept

A blackbody's absolute temperature is doubled. How does its total emitted power change?

According to Stefan–Boltzmann law: $P \propto T^4$

Therefore: $P'/P = (2T/T)^4 = 16$

Answer: Power becomes 16 times.

4.25 Solved Example 5 — Wien's Law

The temperature of a blackbody increases from T to 2T. How does the wavelength corresponding to maximum emission change?

Using: $\lambda_{max}T = $ constant

Therefore: $\lambda'_{max}(2T) = \lambda_{max}T$

Hence: $\lambda'_{max} = \lambda_{max}/2$

Answer: The wavelength of maximum emission becomes half.

4.26 Solved Example 6 — Thermal Conduction

A slab has thickness L. If its thickness is increased to 2L while its area, conductivity and temperature difference remain unchanged, compare the heat-flow rates.

We know: $H = kA\Delta T/L$

Therefore: $H \propto 1/L$

Hence: $H' = H/2$

Answer: The heat-flow rate becomes **half**.

4.27 Important Conceptual Questions

Q1. Why does ice float on water?

Because: **ρ ice < ρ water**

Q2. Why does water below the ice in a frozen lake remain liquid?

Because water has maximum density near 4°C, so the deeper water can remain near 4°C while the surface freezes.

Q3. Why are expansion joints provided in bridges?

To accommodate thermal expansion and contraction and reduce thermal stress

---

Q4. Why does a metal spoon feel colder than a wooden spoon?

Because metal has higher thermal conductivity and transfers heat away from the hand more rapidly.

Q5. Why is a thermos flask silvered?

To reduce heat transfer by radiation

Q6. Why is there a vacuum between the walls of a thermos flask?

To greatly reduce conduction and convection

4.28 NEET/JEE Quick Insights

Insight 1: For a freely expanding rod: **Thermal stress = 0** because there is no constraint.

Insight 2: For a completely constrained rod: **Thermal stress = $Y\alpha\Delta T$**

Insight 3: At 4°C: **ρ water = maximum**

Insight 4: For blackbody radiation: **$P \propto T^4$**

A small increase in absolute temperature can produce a comparatively large increase in radiated power.

Insight 5: For Wien's law: **$\lambda_{max} \propto 1/T$**

Insight 6: For thermal conduction: **$H \propto kA\Delta T/L$**

Therefore:

- Larger k → greater heat flow
- Larger A → greater heat flow
- Larger ΔT → greater heat flow
- Larger L → smaller heat flow

4.29 Quick Revision — Part 4

Concept	Key Result
Anomalous expansion of water	0°C to 4°C: volume decreases
Maximum density of water	Approximately 4°C
Ice density	Less than water
Real expansion	γ_r
Apparent expansion	γ_a
Vessel expansion	γ_v
Relation	$\gamma_a = \gamma_r - \gamma_v$
Constrained thermal expansion	Thermal stress develops
Thermal stress	$Y\alpha\Delta T$
Thermos vacuum	Reduces conduction and convection
Shiny surface	Reduces radiation
Stefan law	$P = \varepsilon\sigma AT^4$
Wien law	$\lambda_{max}T = b$

CHAPTER 10 — PART 4 CONCLUSION

The most important conceptual chain is:

Temperature → Heat → Thermal Expansion → Calorimetry → Change of State → Heat Transfer → Conduction → Convection → Radiation → Thermal Radiation → Cooling → Anomalous Expansion of Water → Thermal Applications

PART 5: ADVANCED NUMERICALS and EXAM PRACTICE

5.1 Chapter-Wide Concept Map

The complete thermal-properties framework can be understood as:

Temperature → Thermal Equilibrium → Heat → Thermal Expansion → Heat Capacity → Specific Heat → Calorimetry → Change of State → Latent Heat → Evaporation → Heat Transfer → Conduction → Convection → Radiation → Blackbody Radiation → Newton's Law of Cooling → Anomalous Expansion of Water

5.2 Advanced Numerical 1 — Composite Heating

A 2 kg metal block has specific heat: **s = 500 J kg⁻¹ K⁻¹.** Its temperature rises from 20°C to 80°C. Find the heat supplied.

Solution

Q = msΔT

Here: **m = 2 kg, s = 500 J kg⁻¹ K⁻¹, ΔT = 80 − 20 = 60 K**

Therefore: **Q = 2 × 500 × 60 = 60000 J**

Answer: Q = 6.0 × 10⁴ J

5.3 Advanced Numerical 2 — Calorimetry

A 100 g metal piece at 100°C is placed in 200 g of water at 20°C. The final temperature is 25°C. Neglecting the heat capacity of the calorimeter, find the specific heat of the metal.

Given

Metal: **m_1 = 0.1 kg, T_1 = 100°C**

Water: **m_2 = 0.2 kg, s_2 = 4200 J kg⁻¹ K⁻¹, T_2 = 20°C**

Final temperature: **T_f = 25°C**

Let specific heat of metal be s_1.

Heat lost by metal:

$$Q_{lost} = m_1 s_1 (T_1 - T_f)$$

Heat gained by water:

$$Q_{gained} = m_2 s_2 (T_f - T_2)$$

Putting the values and using calorimetry:

$$0.1 s_1 (75) = 0.2 (4200)(5)$$

Therefore:

$$7.5\, s_1 = 4200$$

Hence:

$$s_1 = 560\ J\ kg^{-1}\ K^{-1}$$

Answer: 560 J kg⁻¹ K⁻¹

5.4 Advanced Numerical 3 — Thermal Expansion

A 1 m steel rod has: **α = 1.2 × 10⁻⁵ K⁻¹.** The temperature increases by 200 K. Find its increase in length.

Using: **ΔL = αLΔT**

Therefore: $\Delta L = (1.2 \times 10^{-5})(1)(200) = 2.4 \times 10^{-3}$ **m**
Hence: $\Delta L = 2.4$ **mm**
Answer: **2.4 mm**

5.5 Advanced Numerical 4 — Volume Expansion

A solid cube has volume: $V = 0.5\ m^3$
Its coefficient of linear expansion is: $\alpha = 2 \times 10^{-5}\ K^{-1}$
Temperature increases by: **100 K.** Find the increase in volume.
For an isotropic solid: $\gamma = 3\alpha$
Therefore: $\gamma = 6 \times 10^{-5}\ K^{-1}$
Now: $\Delta V = \gamma V \Delta T = (6 \times 10^{-5})(0.5)(100) = 3 \times 10^{-3}\ m^3$
Answer: $\Delta V = 3 \times 10^{-3}\ m^3$

5.6 Advanced Numerical 5 — Thermal Stress

A rod has: $Y = 2 \times 10^{11}$ **Pa,** $\alpha = 1 \times 10^{-5}\ K^{-1}$**.** It is heated by: $\Delta T = 50$ **K** and expansion is completely prevented. Find the stress.
Using: **Stress** $= Y\alpha\Delta T$
Therefore: **Stress** $= (2 \times 10^{11})(1 \times 10^{-5})(50) = 1 \times 10^{8}$ **Pa**
Answer: **Thermal stress** $= 1 \times 10^{8}$ **Pa**

5.7 Advanced Numerical 6 — Conduction

A wall has: $k = 0.8\ W\ m^{-1}\ K^{-1}$, $A = 10\ m^2$, $L = 0.2$ **m.** Temperature difference: $\Delta T = 20$ **K**
Find the rate of heat transfer.
Using: $H = kA\Delta T/L$
Therefore: $H = (0.8)(10)(20)/(0.2) = 800$ **W**
Answer: $H = 800$ **W**

5.8 Advanced Numerical 7 — Stefan–Boltzmann Scaling

A blackbody radiates power P at temperature T. If its temperature becomes: **3T,** what is the new power?
Since: $P \propto T^4$
Therefore: $P'/P = (3T/T)^4 = 81$
Answer: $P' = 81P$

5.9 Advanced Numerical 8 — Wien's Law

A blackbody has: $\lambda_{max} = 600$ **nm.** Estimate its temperature.
Convert: $600\ nm = 600 \times 10^{-9}\ m$
Using: $\lambda_{max}T = 2.898 \times 10^{-3}$
Therefore: $T = 2.898 \times 10^{-3}/(600 \times 10^{-9}) \approx 4830\ K$
Answer: $T \approx 4.83 \times 10^{3}\ K$

5.10 Advanced Numerical 9 — Latent Heat

How much heat is required to convert 2 kg of ice at 0°C into water at 0°C?
Since only melting occurs:
$Q = mL_f$

Therefore: $\mathbf{Q = 2(3.34 \times 10^5) = 6.68 \times 10^5\ J}$

Answer: $\mathbf{Q = 6.68 \times 10^5\ J}$

5.11 Advanced Numerical 10 — Ice to Water

Find the heat required to convert 2 kg of ice at 0°C into water at 50°C.

Step 1: Melt ice

$$\mathbf{Q_1 = mL_f}$$

Step 2: Heat water

$$\mathbf{Q_2 = mc\Delta T}$$

Therefore: $\mathbf{Q\ total = mL_f + ms\ \Delta T}$

Substituting:

$\mathbf{Q\ total = 2(3.34 \times 10^5) + 2(4200)(50) = 6.68 \times 10^5 + 4.20 \times 10^5}$

Therefore: $\mathbf{Q\ total = 1.088 \times 10^6\ J}$

Answer: $\mathbf{Q\ total = 1.088 \times 10^6\ J}$

5.12 Conceptual Questions

Q1. Why does a metal spoon become hot when placed in hot tea?

Because heat is transferred through the metal by conduction.

Q2. Why can radiation transfer heat through vacuum?

Because electromagnetic waves do not require a material medium.

Q3. Why are cooking utensils generally made of metals?

Because metals generally have relatively high thermal conductivity.

Q4. Why are handles of cooking utensils made from insulating materials?

To reduce heat transfer to the user's hand

Q5. Why does a pressure cooker cook food faster?

Because increased pressure raises the boiling point of water.

Q6. Why does sweating cool the body?

Evaporation preferentially removes higher-energy molecules from the sweat.

Q7. Why does water at 4°C sink in a lake?

Because it has maximum density.

Q8. Why does ice form at the surface of a lake first?

Water below 4°C becomes less dense, so the colder water remains near the surface.

5.13 NEET/JEE Rapid-Fire Concepts

1. If $\mathbf{T \rightarrow 2T}$:, **Blackbody power → 16 times**
2. If $\mathbf{T \rightarrow 3T}$: **Blackbody power → 81 times**
3. If $\mathbf{T \rightarrow 2T}$: $\mathbf{\lambda max \rightarrow \lambda max/2}$
4. If thickness of slab doubles: **Heat-flow rate → half**
5. If area doubles: **Heat-flow rate → double**
6. If thermal conductivity doubles: **Heat-flow rate → double**
7. If radius of a uniformly heated hole increases: **Hole expands**
8. At 4°C: **Density of water is maximum**
9. For a freely expanding body: **Thermal stress = 0**

10. For a completely constrained body: **Thermal stress = $Y\alpha\Delta T$**

5.14 Common Formula Traps

Trap 1

Do not use: **$Q = ms\Delta T$** during a pure phase change.
Use: **$Q = mL$**

Trap 2

Do not use Celsius in: **$P = \sigma AT^4$**
Use Kelvin.

Trap 3

Remember:
$\beta = 2\alpha$
$\gamma = 3\alpha$

Trap 4

For a constrained rod:
Stress = $Y\alpha\Delta T$ not merely: **$\alpha\Delta T$** because $\alpha\Delta T$ is strain.

Trap 5

For water:
Maximum density → 4°C not 0°C.
